System Level Analysis of Hydrogen Storage Options

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Overview

Timeline

- Project start date: Oct 2009
- Project end date: N/A
- Project continuation and direction determined annually by DOE

Barriers

- H_2 Storage Barriers Addressed:
  - A: System Weight and Volume
  - B: System Cost
  - C: Efficiency
  - E: Charging/Discharging Rates
  - J: Thermal Management
  - K: Life-Cycle Assessments

Budget

- FY15 DOE Funding: $480 K
- FY16 DOE Funding: $480 K

Partners/Interactions

- Storage Systems Analysis Working Group (SSAWG)
- PNNL, Tank OEMs
- Delivery Team
- Hydrogen Storage Engineering Center of Excellence (HSECoE): Ford, LANL
- Strategic Analysis

Relevance and Impact

Develop and use models to analyze the on-board and off-board performance of physical and material-based automotive hydrogen storage systems

- Conduct independent systems analysis for DOE to gauge the performance of H_2 storage systems
- Provide results to material developers for assessment against system performance targets and goals and help them focus on areas requiring improvements
- Provide inputs for independent analysis of costs of on-board systems.
- Identify interface issues and opportunities, and data needs for technology development
- Perform reverse engineering to define material properties needed to meet the system level targets

Impact of FY2016 work

- Validated and updated the 700-bar compressed hydrogen analysis for the DOE 2015 Program Record (Onboard Storage Performance and Cost)
- Investigated alternate tank designs and material approaches that can lead to 7-23% reduction in carbon fiber requirement
- Identified material attributes for hybrid cH_2-high pressure metal hydride (HPMH) tanks
- Determined HPMH capacities and kinetics for >45% reduction in CF usage

Approach

- Develop thermodynamic and kinetic models of processes in physical, complex metal hydride, sorbent, and chemical H_2 storage systems
  - Address all aspects of on-board and off-board storage targets, including capacity, charge/discharge rates, emissions, and efficiencies
  - Perform finite-element analysis of compressed hydrogen storage tanks
  - Assess improvements needed in materials properties and system configurations to achieve storage targets
- Select model fidelity to resolve system-level issues
  - On-board system, off-board spent fuel regeneration, reverse engineering
  - Conduct trade-off analyses, and provide fundamental understanding of system/material behavior
  - Calibrate, validate, and evaluate models
- Work closely with DOE technology developers, HSECoE and others in obtaining data, and provide feedback
- Participate in SSAWG meetings and communicate approach and results to foster consistency among DOE-sponsored analysis activities

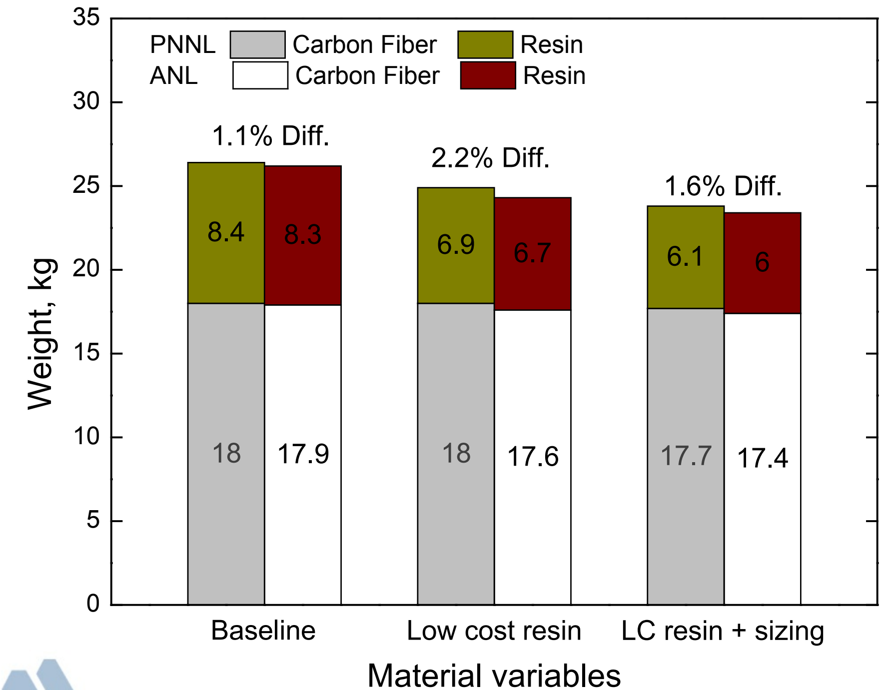
Summary: FY2016 Accomplishments and Progress

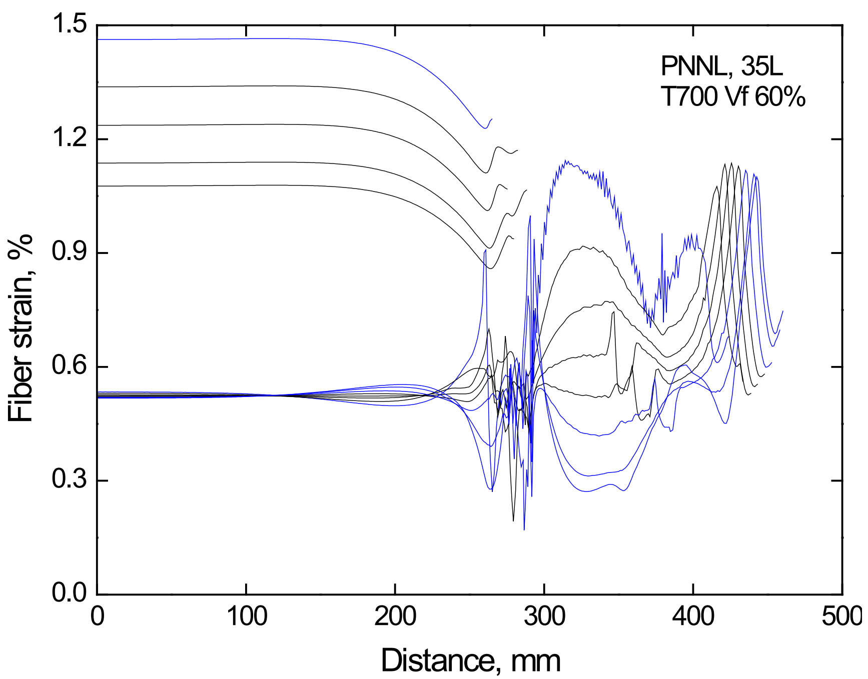
1. Physical storage
   - Validated ABAQUS models for tanks with low cost resin and alternate sizing (PNNL/HL) and updated DOE Program Record
   - Conducted ABAQUS simulations of Mirai 60-L front (L/D = 2.8-3.0) and rear tanks (L/D = 1.7)
   - Analyzed full size tanks with features of Mirai design concept to determine CF reduction opportunity
2. H_2 storage in high-pressure metal hydrides
   - Identified desirable thermodynamic attributes for using HPMH in hybrid cH_2 tanks
   - Determined HPMH material capacity and kinetic requirement to match performance of 700-bar cH2 tanks in 350-bar hybrid tanks
3. H_2 storage in sorbents
   - Published paper in IJHE on reverse engineering to determine material properties needed to meet system targets including well-to-tank (WTT) efficiency
   - Updating the reverse engineering model with HSECoE (Ford) thermal conductivity and H_2 uptake data for pellets
4. Chemical hydrogen storage
   - Validate and update reactor and BOP models utilizing HSECoE data (ongoing)

Data Validated Model

Validated ABAQUS-WCM FEA model using data for PNNL/Hexagon Lincoln burst tests on 35-L tanks*

- The highest strain occurs in the cylinder section, consistent with burst tests
- Determined the composite translation efficiency for T700/epoxy (conventional) tanks
- Applied the same translation efficiency to tanks with low cost resin and low cost resin/alternate sizing.
  - Fiber volume fraction and resin density differ from conventional tank
- FEA results show good agreement with test data

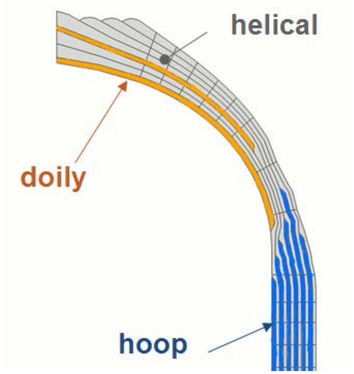


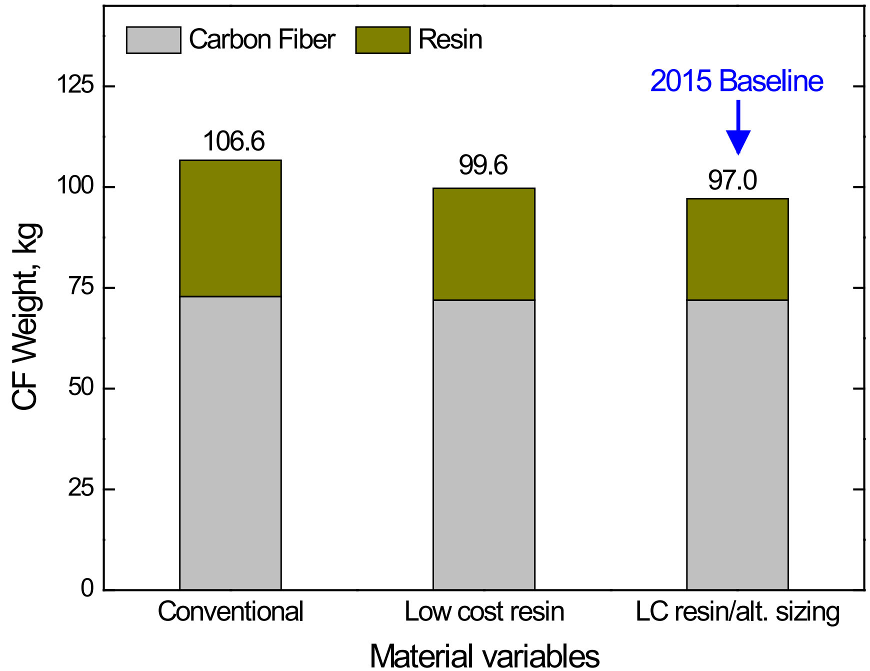


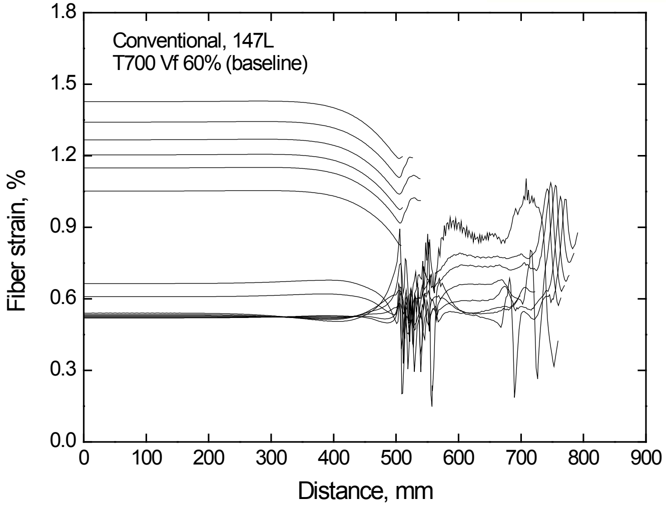
*David Gotthold, "Enhanced Materials and Design Parameters for Reducing the Cost of Hydrogen Storage Tanks," 2015 AMR

2015 DOE Onboard Storage Performance Record

- Conventional tank requires106.6 kg CF composite. Two alternate tanks weigh less, primarily due to reduction in the weight of resin.
- The 2015 baseline tank requires 97 kg composite resulting in a system gravimetric capacity of 1.40 kWh/kg system, and volumetric capacity of 0.81 kWh/L system*. Compared to the 2013 baseline, the changes include:
  - Replacing the doilies with additional helical windings
  - Using low cost resin which also has lower density than epoxy
  - Reducing the number of BOP parts through component integration





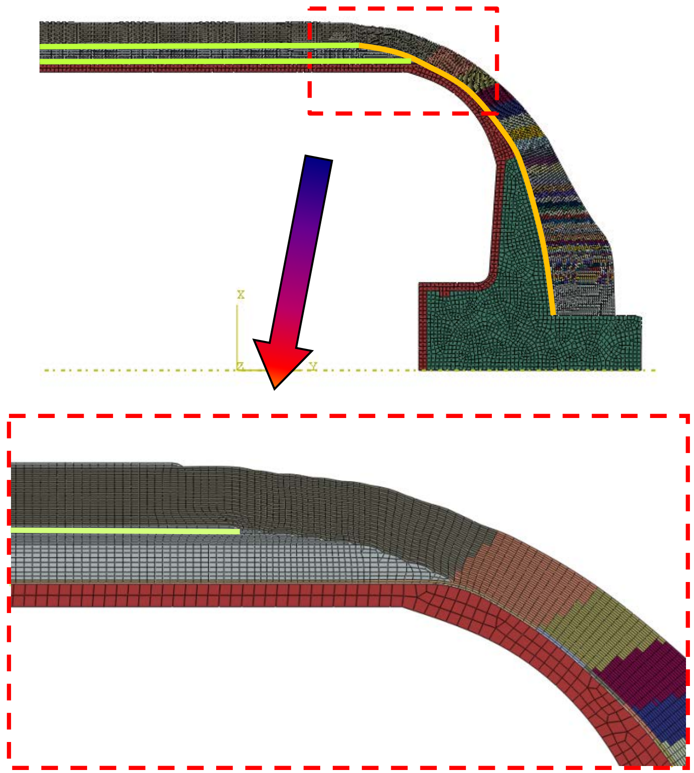


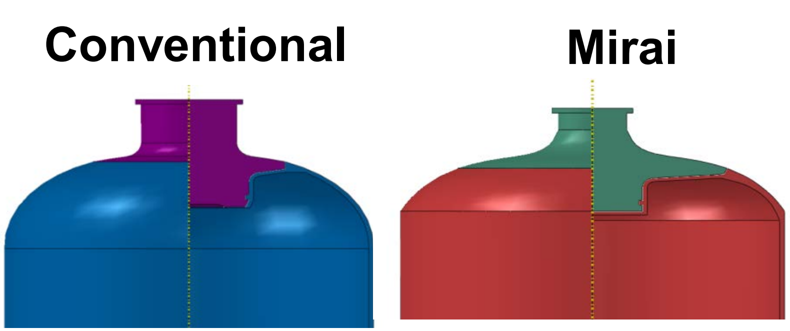
* DOE Hydrogen and Fuel Cells Program Record, Record # 15013, September 30, 2015. http://www.hydrogen.energy.gov/pdfs/15013_onboard_storage_performance_cost.pdf

Evaluation of Alternate Design Concepts

Conducted ABAQUS FEA simulations to evaluate "Mirai" tank concepts*

1. **Alternate Liner Geometry (ALG)**
   - Liner with sharp transition from cylinder to dome
   - Elimination of high-angle helical winding
2. **Alternate Winding Scheme (AWS)**
   - One helical layer over the entire liner
   - Concentrated hoop winding over the cylinder
   - Helical winding over cylinder and dome
3. **Alternate Boss Design (ABD)**
   - Smaller diameter boss with longer flange
4. **Alternate Carbon Fiber (ACF)**
   - T720 CF (higher strength than T700)





**References*:

- Yamashita, A., Kondo, M., Goto, S., and Ogami, N., "Development of High-Pressure Hydrogen Storage System for the Toyota "Mirai"," SAE Technical Paper 2015-01-1169, 2015, doi:10.4271/2015-01-1169

- Hirokazu Otsubo and Shiro Nishibu, US Patent US20130299505A1, November 2013

Evaluation of Alternate Tank Design Concepts

ABAQUS simulations of 60-L tank, L/D ~ 2.8, GF layer for impact resistance, foam

Tank	Liner	Winding	Boss	Composite	Remarks
1	CONV	CONV	CONV	T700/epoxy	Conventional tank with smooth liner, baseline winding and boss, and T700 composite
2	ALG	AWS	ABD	T700/epoxy	Alternate liner, winding and boss, T700 composite
3	ALG	AWS	ABD	T720/epoxy	Tank 2 with T720 composite
6	ALG	AWS	CONV	T700/epoxy	Tank 2 with conventional boss

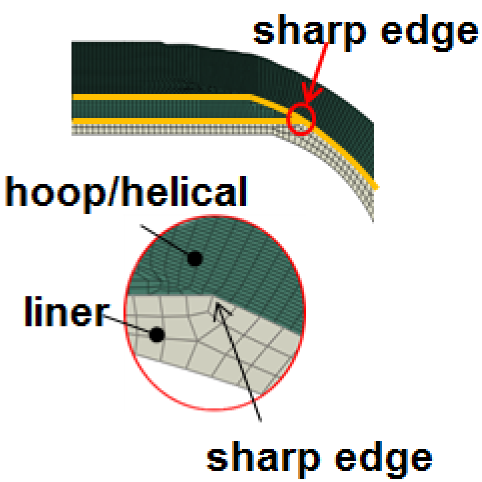
- Alternate design concepts reduce the composite weight by 7.2% (tank 2 versus tank 1)
- Alternate carbon fiber (T720) reduces the composite weight by 20.2% (tank 3 versus tank 2)
- Boss with smaller diameter and longer flange did not show noticeable effect (tank 6 vs. tank 2; ~5% reduction in amount of helical windings in SAE paper)

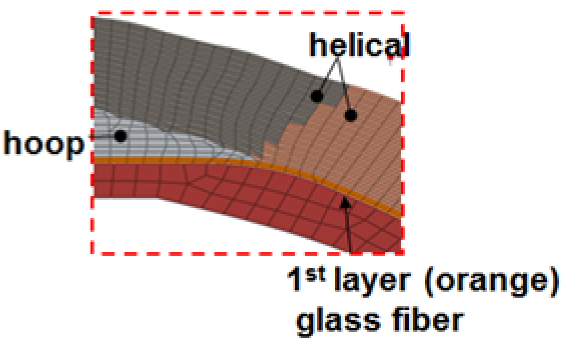
Tank	Composite (kg)			Others (kg)			Tank Total (kg)	Mirai Tank (kg)
	Hoop	Helical	Total	Bosses	Liner/GF/Foam	Total		
1	17.7	25.3	43.0	3.8	7.4	11.2	54.2	
2	15.2	24.7	39.9	4.8	7.4	12.2	52.1	
3	12.0	21.2	33.2	4.8	7.4	12.2	45.4	42.8

Addressing Stress Concentration at Cylinder/Dome Interface

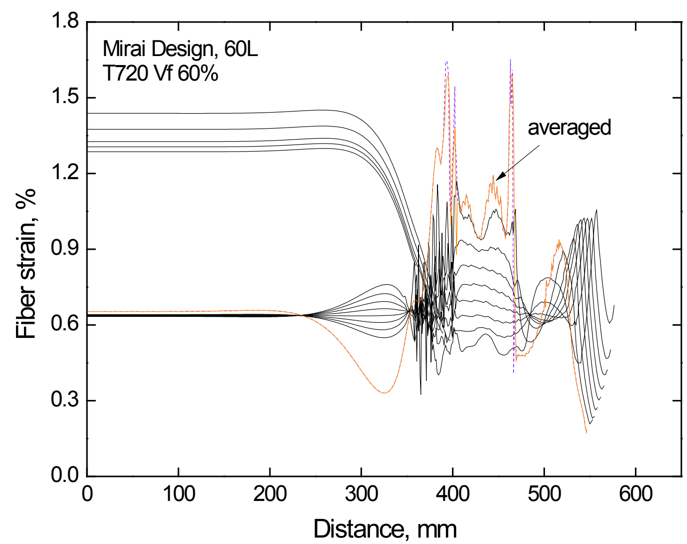
To relax stress concentration at the cylinder/dome interface, proposed and analyzed the concept of winding the innermost helical layer with glass fiber which has higher failure strain (>3.5%) than carbon fiber (<2.0%)

- Using GF for the 1st helical layer reduces the composite weight by 2-3% and CF weight by 5-6%
- Since GF costs significantly less than CF, there is a net savings in material cost at the expense of incurring additional winding cost*





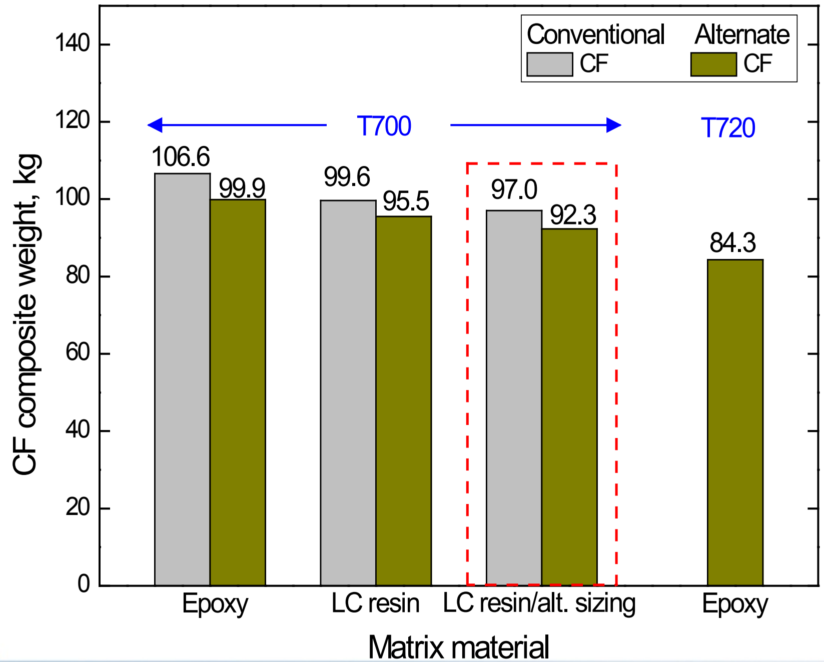
Tank	Composite Material	1st helical layer: CF			1st helical layer: GF			
		Hoop	Helical	Total	Hoop	Helical	CF	CF + GF
2	T700/epoxy	15.2	24.7	39.9	15.3	23.7	37.6	39.0
3	T720/epoxy	12.0	21.2	33.2	12.1	20.3	30.9	32.4
4	T700/lc resin	14.0	24.1	38.1	14.1	23.2	35.9	37.3
5	T700/lc resin, alt. sizing	13.8	23.0	36.8	14.3	22.1	35.0	36.4



*No existing standards for use of mixed carbon fibers and glass fibers

Alternate Tank Designs for 5.6 kg H_2 (147 L, L/D = 3)

Tank	Liner	Winding	Boss	Composite	Remarks
7	CONV	CONV	CONV	T700/epoxy resin	Reference tank in 2015 storage performance record
7A	ALG	AWS	ABD	T700/epoxy resin	Alternate reference tank design
8	CONV	CONV	CONV	T700/low-cost resin	2015 reference tank design with low-cost resin
8A	ALG	AWS	CONV	T700/low-cost resin	Alternate tank design with low-cost resin
9	CONV	CONV	CONV	T700/low-cost resin/alternate sizing	2015 reference tank design with low-cost resin and alternate sizing
9A	ALG	AWS	ABD	T700/low-cost resin/alternate sizing	Alternate tank design with low-cost resin and alternate sizing
10A	ALG	AWS	ABD	T720/epoxy resin	Alternate tank design with T720/epoxy composite

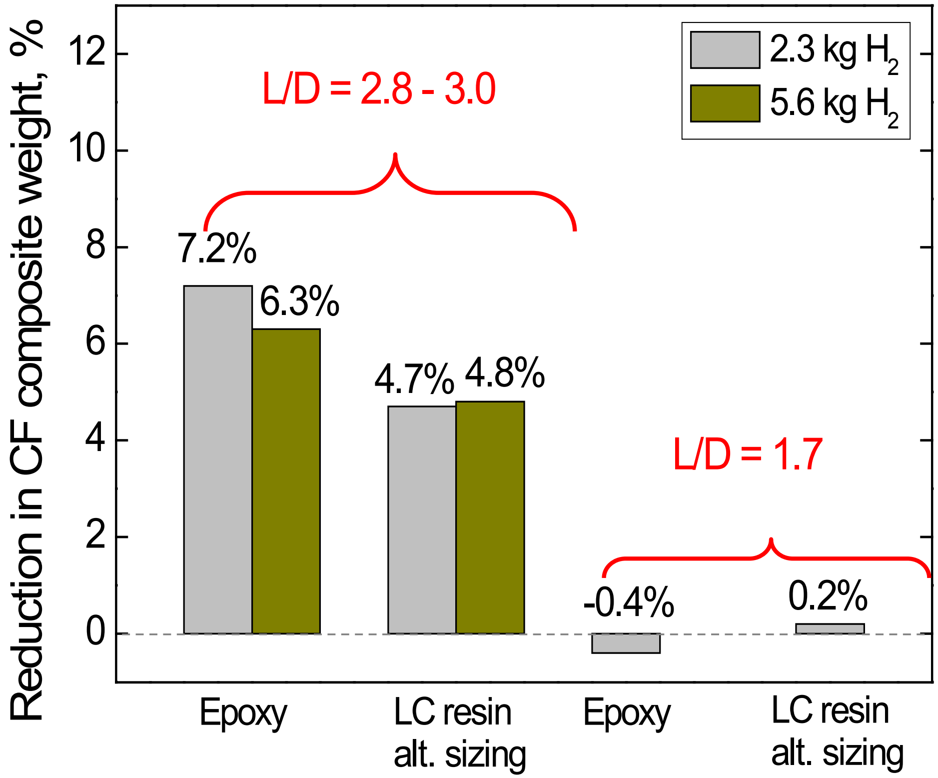


Potential CF reductions with alternate tank design and fiber

- 6.3% in tanks reinforced with T700/epoxy resin
- 4.8% in tanks reinforced with T700/low-cost resin + alternate sizing
- 21% in tanks reinforced with T720/epoxy (vs. T700/epoxy)

Effect of Tank Length-to-Diameter Ratio

- Results for the "Mirai" front tank (L/D = 2.8) and full sized tanks (L/D = 3.0) show that the alternate design concepts could reduce the CF amount by 5 to 7%. There is a larger reduction in hoop than in helical windings
- Analysis carried out for the "Mirai" rear tank (L/D = 1.7), however, shows practically no difference in the total amount of CF usage as compared to a conventional tank. There is a large reduction in helical winding that is offset by a larger increase in hoop winding.



ABAQUS results for 2.3-kg H_2 front (L/D = 2.8) and rear (L/D = 1.7) tanks

Front Tank (60L)	Fiber	CF Composite Weight, kg		
		Cylinder	Dome	Total
Traditional	T700	34.6	8.4	43.0
Mirai*	T700	32.7	7.2	39.9
Difference (Mirai)		-1.9	-1.2	-3.1

Rear Tank (62L)	Fiber	CF Composite Weight, kg		
		Cylinder	Dome	Total
Traditional	T700	29.52	15.34	44.86
Mirai*	T700	31.76	13.4	45.17
Difference (Mirai)		2.24	-1.94	+0.3

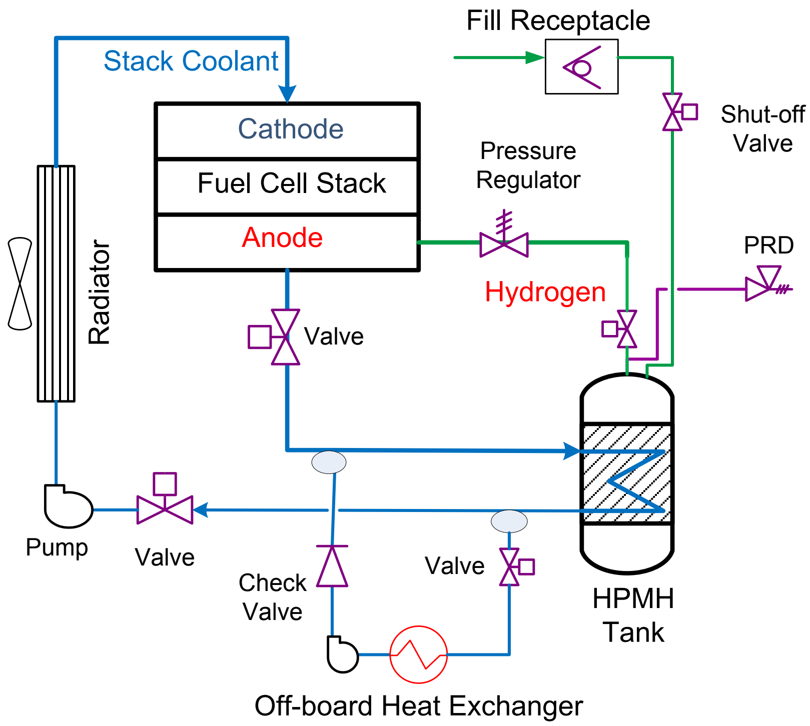
High Pressure/Low Enthalpy Metal Hydrides (HPMH)

Defined as metal hydrides that are thermodynamically unstable at room temperature and pressure but can be formed at elevated pressures

- Particularly suitable for augmenting performance of compressed hydrogen storage tanks (See, e.g., Mori, Haraikawa, Kobayashi, Shinozawa, Matsunaga, Kubo, Toh, and Tsuzuki, "High-Pressure Metal Hydride* Tank for Fuel Cell Vehicles," IPHE International Hydrogen Storage Technology Conference, 19-22 June 2005, Luca Italy)

350-bar Type 4 Hybrid Storage Tank

- Performance improvement: Feasibility of reaching the volumetric capacity of the reference Type 4 700-bar cH_2 tank
- Cost reduction: Significantly reduce the carbon fiber content to less than needed in the reference system



Storage System	Compressed H_2		Hybrid
Storage Pressure	700 bar	350 bar	350 bar
Volumetric Capacity	24.4 g/L	17.7 g/L	24.6 g/L
Gravimetric Capacity	4.2 wt%	5.4 wt%	4.3 wt%
Carbon Fiber	97 kg	62 kg	51 kg

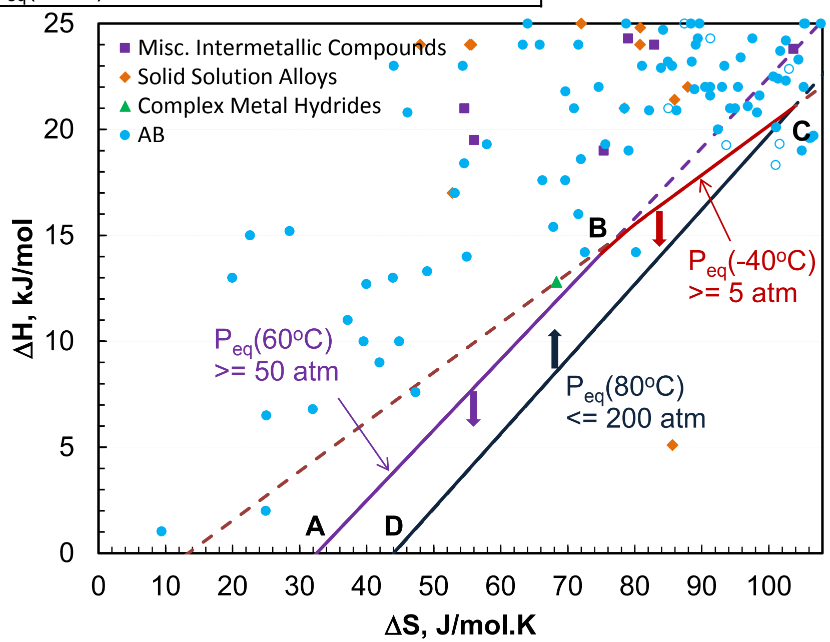
HPMH: Ti-Cr-Mn alloy (AB_2 laves phase); LPMH: Ti-Cr-V alloy

High Pressure Metal Hydrides: Thermodynamic Requirements

System Target	Approach	Material Requirement
Refuel at 350 bar (P_c)	Limit the temperature to 80°C (Type 4 liner)	For reasonable charge kinetics, desirable to have $\Delta P(P_c-P_{eq}) > 150$ bar The equilibrium pressure, P_{eq}(80°C) should be less than 200 bar
Ability to start FC at -40°C	Maintain gaseous H_2 in tank at -40°C	Equilibrium pressure should be above the minimum delivery pressure at all temperatures. P_{eq}(-40°C) > 5 bar
Discharge MH using stack coolant as the heat source	Stack coolant operating temperature varies between 60 and 90°C	MH should discharge at the lowest operating coolant temperature For reasonable discharge kinetics, desirable to have $\Delta P(P_{eq}-P_d) > 50$ bar P_{eq}(60°C) > 50 bar

Solid lines define the acceptable HPMH thermodynamic map. For given ΔS, ΔH is limited by

- Boundary AB: Requirement to discharge MH using stack coolant at 60°C as heat source
- Boundary BC: Requirement to maintain tank pressure above 5 bar at -40°C
- Boundary CD: Requirement to maintain reasonable ΔP while refueling tank to 350 bar at 80°C

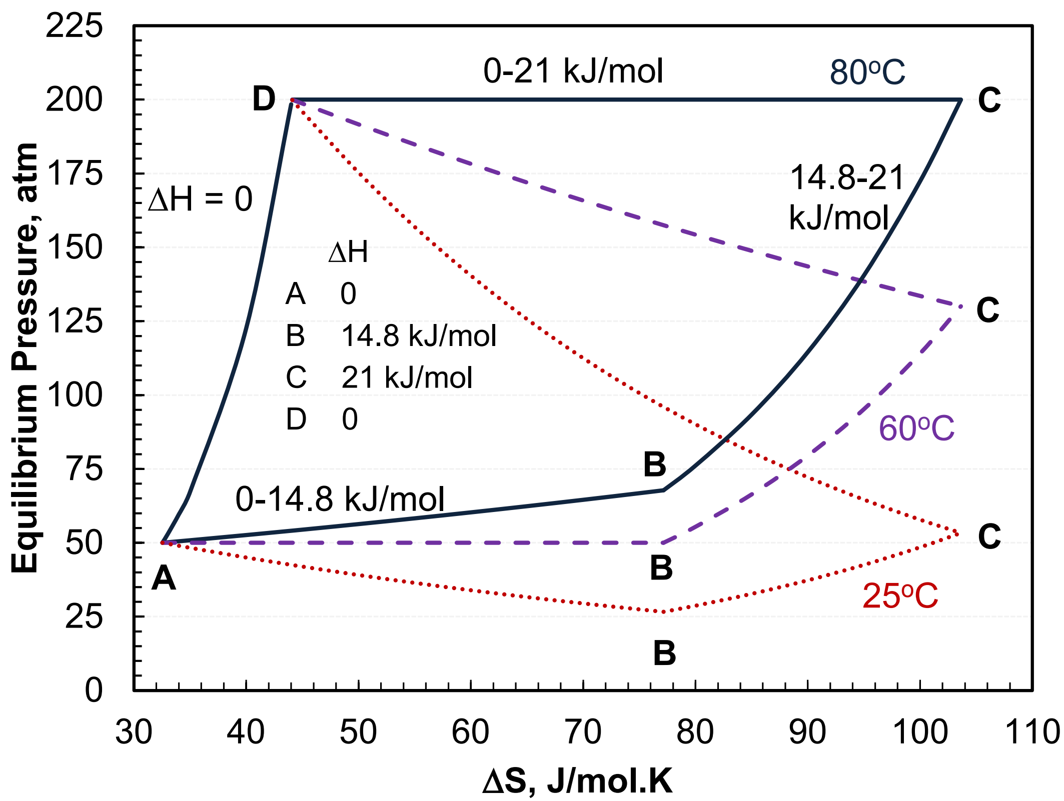


Solid symbols: Hydpark database;
Open Symbols: IJHE 39 (2014) 5818-5851;
AB5: $CeNi_5$, 14.2 kJ/mol; AB2: $Ti_{1.2}Cr_{1.9}Mn_{0.1}$, 20.1 kJ/mol

High Pressure Metal Hydrides: Operating Pressures

Material ID	ΔH kJ/mol	ΔS J/mol.K	$P_{eq}(25^oC)$ bar	$P_{eq}(60^oC)$ bar	$P_{eq}(80^oC)$ bar
A	0	33	50	50	50
B	14.8	77.2	26.6	50	67.8
C	21	103.6	53.3	130	150
D	0	44.1	200	200	200

- Material A charges if P > 50 bar and discharges if P < 50 bar
- Material B begins to charge after the tank is refueled to 67.8 bar at 80^{o}C, and doesn't discharge until P drops below 26.6 bar at 25^{o}C
- Material C begins to charge after the tank is refueled to 200 bar at 80^{o}C, and doesn't discharge until P drops below 53.3 bar at 25^{o}C
- Material D charges if P > 200 bar and discharges if P < 200 bar

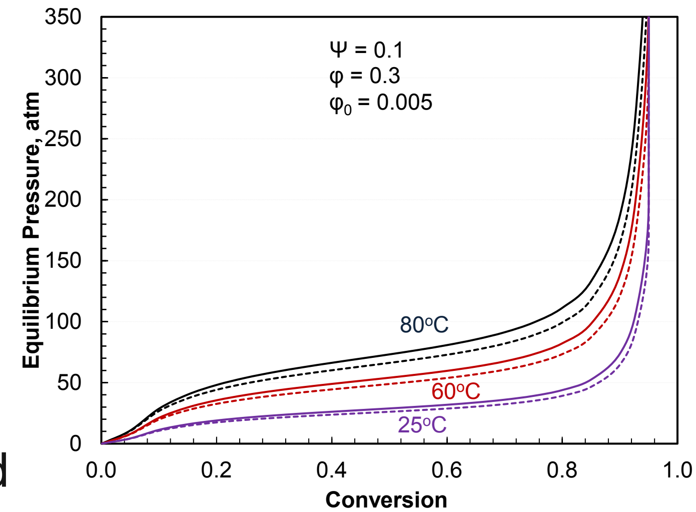


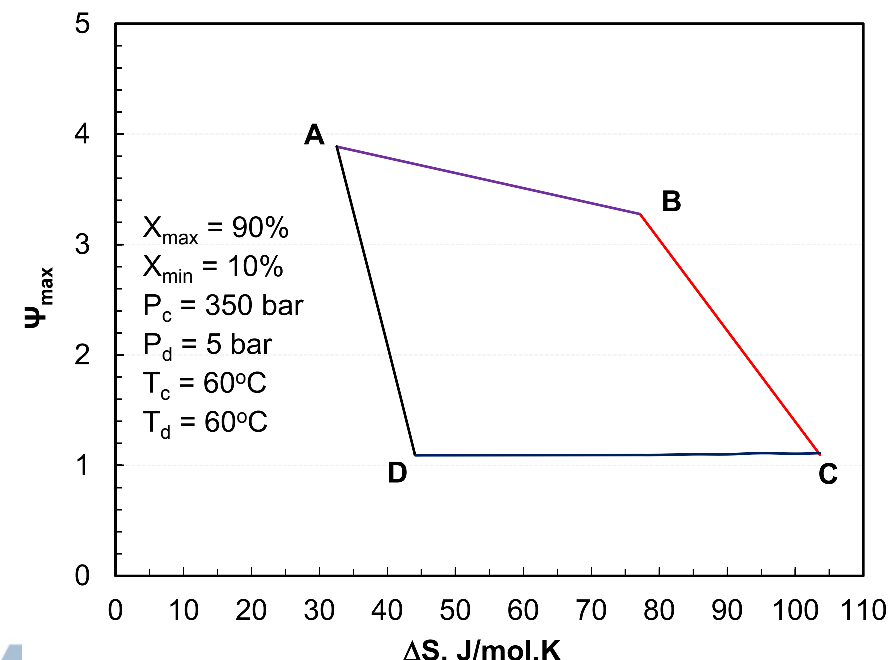
HPMH: Pressure-Composition-Temperature (PCT) Isotherms

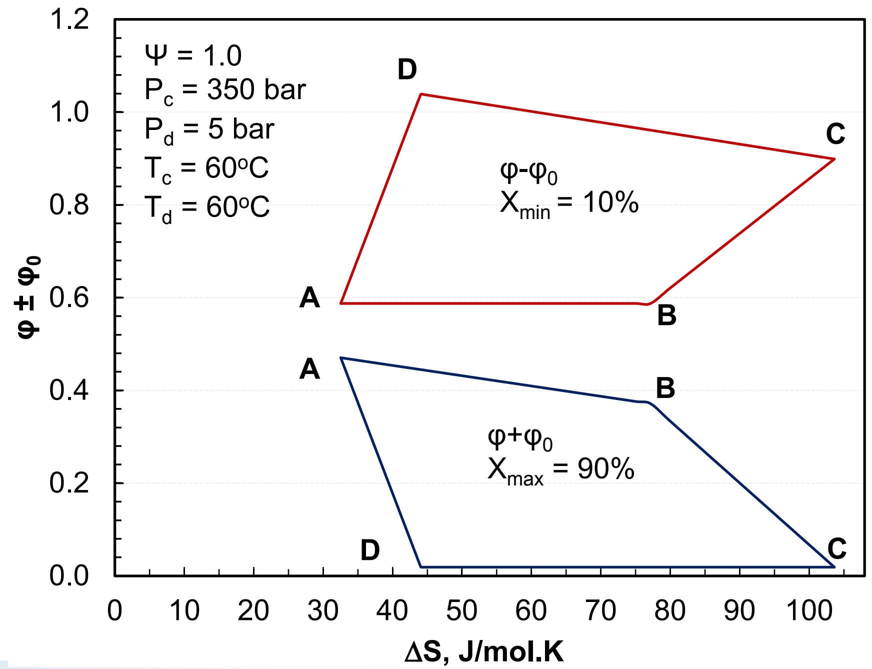
- PCT isotherms* with hysteresis (Ψ) and sloping plateau pressure (φ, φ_0)

$$ln(P_{eq}) = \frac{\Delta H}{RT} - \frac{\Delta S}{R} + (\varphi \pm \varphi_0)\tan[\pi\left(\frac{x}{x_0} - \frac{1}{2}\right)] \pm \frac{\Psi}{2}$$

- Allowable hysteresis (Ψ) determined by the desired min. and max. conversion, operating P and T during charging and discharging, and material thermodynamic properties (ΔH and ΔS)
- Allowable plateau slope is determined by desired 90% conversion (X_{max}) during charging



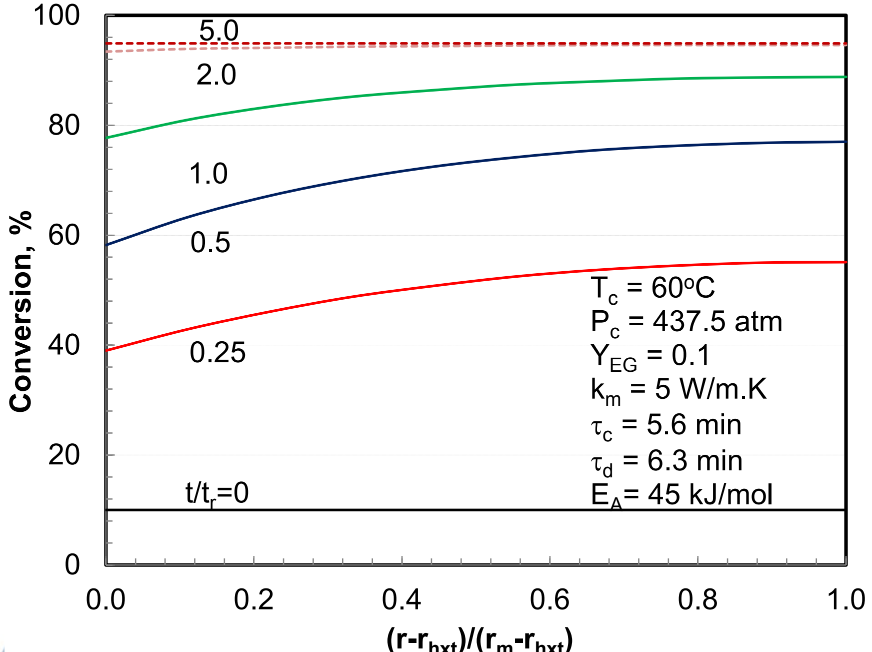


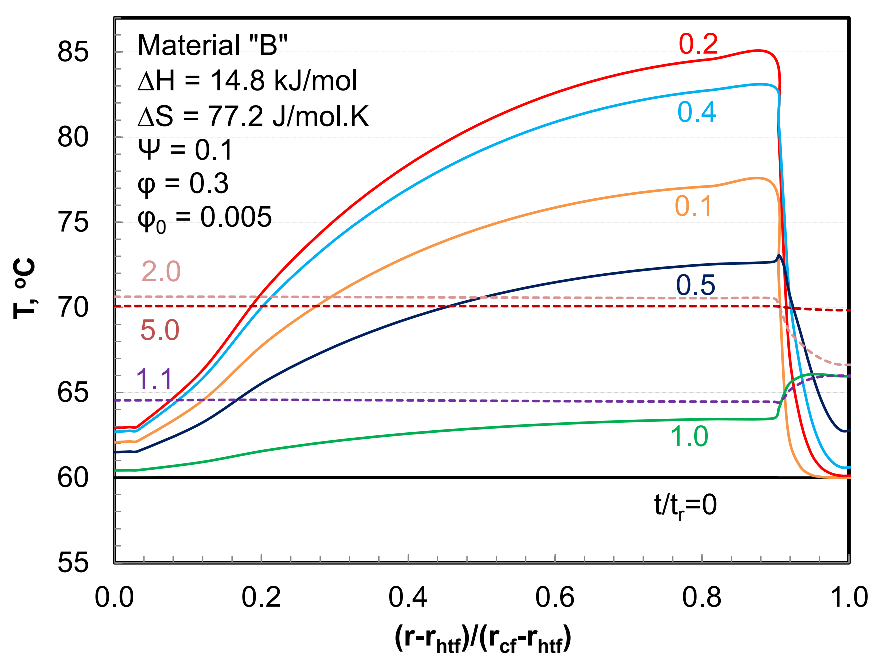


*T Nishizaki, K. Miyamoto, and K. Yoshida, J. Less-Common Metals, 89 (1983) 559-566.

Dynamic Refueling of Hybrid Tank

- Model considers a repeat unit of the metal hydride bed, representing heat transfer fluid ($\hat{r} = {}^{(r-r_{htf})}/_{(r_{cf}-r_{htf})} < 0$), heat exchanger tube ($\hat{r} < 0.1$), metal hydride and sintered metal tubes ($\hat{r} < 0.95$), HDPE liner ($\hat{r} < 0.97$), and carbon fiber ($\hat{r} < 1$).
- Constant pressure refueling at 1.5 kg/min average fill rate (t_r = 224 s).
- Conversion at outer periphery leads that at region around the heat exchanger tube
- **HPMH continues to absorb H_2 after the refueling event (t/t_r = 1) with conversion approaching the equilibrium limit at the prevailing pressure**

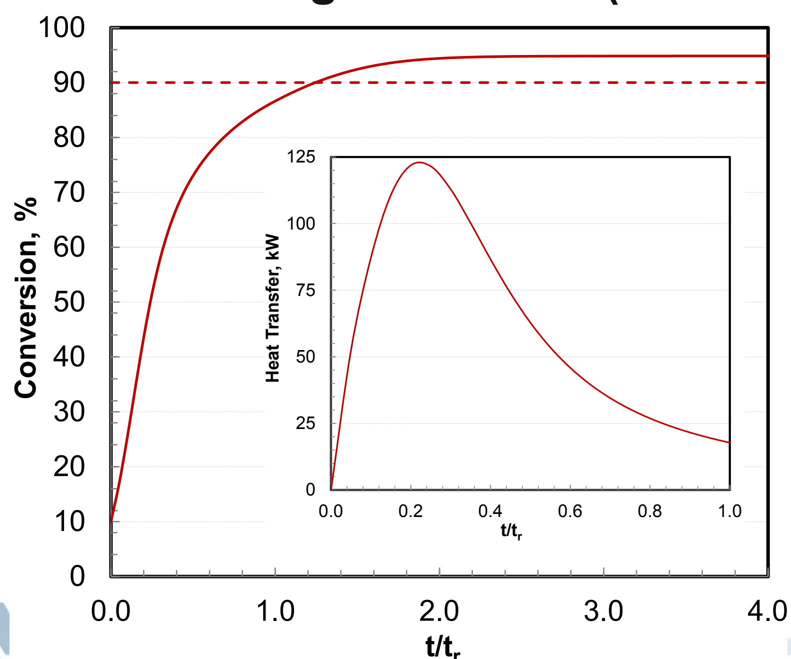


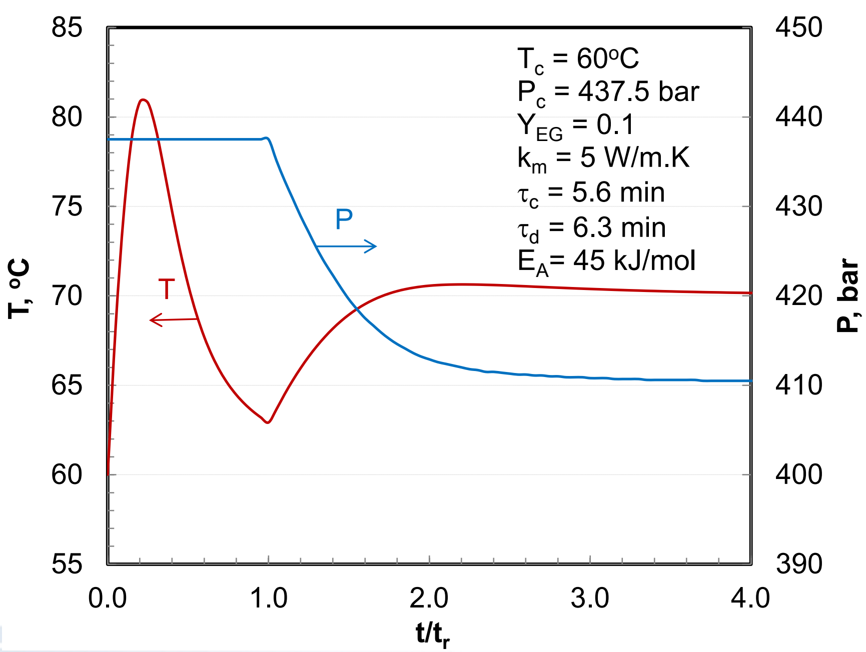


Dynamics of Refueling

Charging at constant pressure below the 25% threshold

- Post refueling, the temperatures rises and the tank pressure declines as the HPMH continues to convert
- During refueling, HPMH first heats to reach a peak temperature and then cools because of heat transfer to the coolant
- For maximum capacity and HPMH utilization, refueling P selected such that the tank P relaxes to the design P (350 bar) after cooling to ambient temperature. This sets the lower refueling P limit. The upper refueling P limit is dictated by the SAE specified safety factor.
- **External cooling circuit required if the on-board radiator cannot handle 62 kW average heat load (80.4 MJ total)**

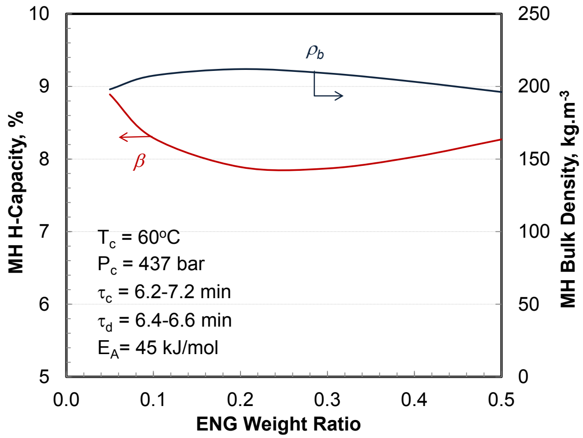




Sensitivity Study

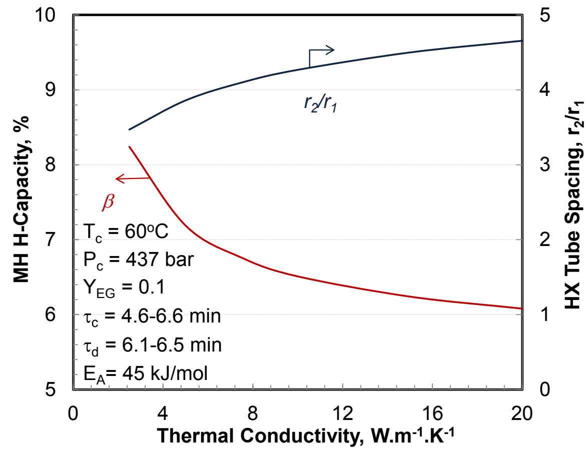
Randomly Mixed and Compacted HPMH and ENG

- 0.25 ENG/HPMH weight ratio about optimum



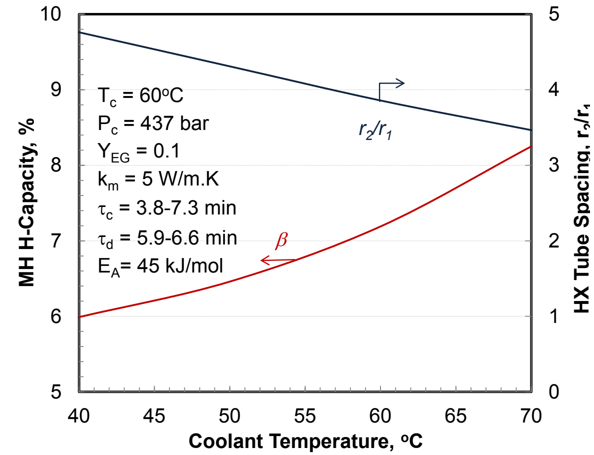
Layered and Compacted HPMH and 10% ENG

- β<6.5% if k_m>10 W/m.K



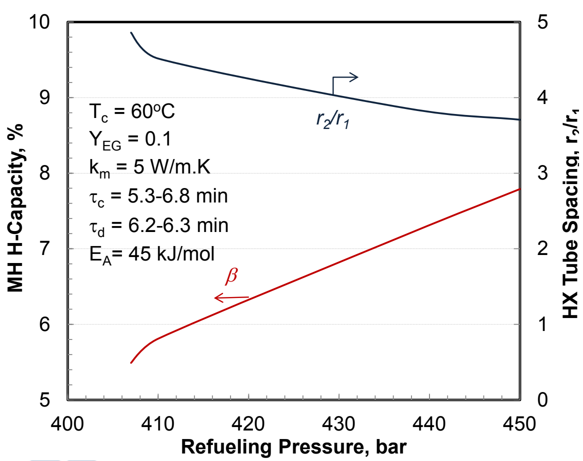
Coolant Temperature

- Tube spacing controlled by heat transfer, not charge kinetics



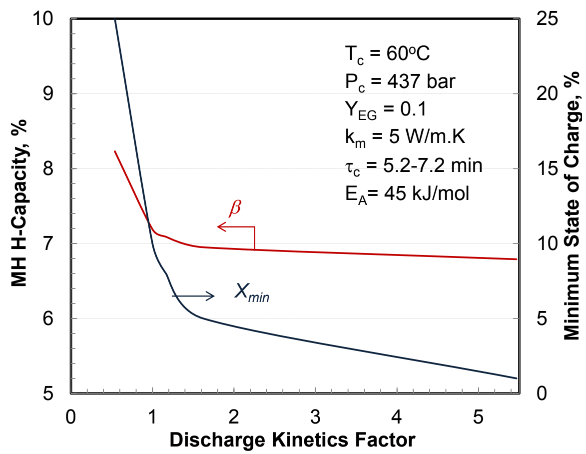
Refueling Pressure

- Best to refuel at lowest pressure that leads to 350 bar



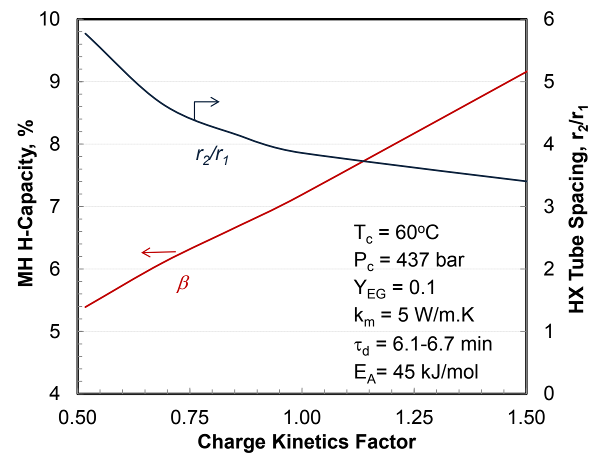
Discharge Kinetics

- Disadvantage of slower kinetics far outweighs the advantage of faster kinetics



Charge Kinetics

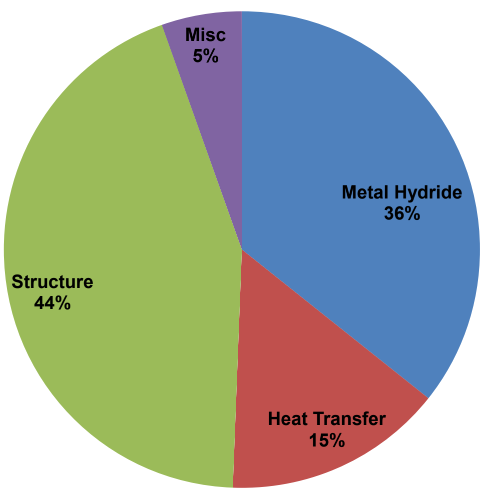
- 2X reduction in charge kinetics is acceptable because of the accompanying rise in bed T



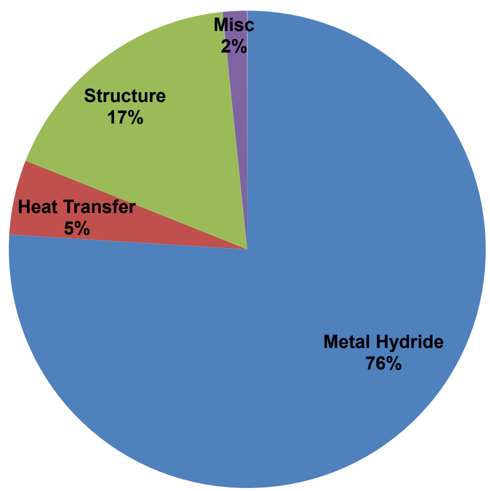
Summary: Desired HPMH Material Properties

Variables	Related Variables	Reference Values	Constraints
UMH Intrinsic Capacity		5.8% H capacity	4.3 wt% gravimetric
Fill Ratio	Bulk Density	80.6% bed porosity	24.6 g/L volumetric
	Thermal Conductivity	292 kg/m^3 HPMH bulk density	
		5 W/m.K bed conductivity	
Desorption Kinetics	X_{min} = 10%	τ_d = 6.2 min	1.6 g/s min full flow
Sorption Kinetics	X_{max} = 93%	τ_c = 6.7 min	X_{min} to X_{max} in 3.7 min
HX Tube Spacing	Number of HX Tubes	r_2/r_1 = 4.5	1.5 kg/min refueling
		58 U tubes	
Refueling Pressure	Storage Pressure	410 atm	350 bar design pressure
			25% overpressure limit
Mass of UMH	Mass of Expanded	46.5 kg HPMH	5.6 kg usable H_2
	Natural Graphite	4.7 kg EG	3.4 kg as cH_2
			2.5 kg H_2 in HPMH

Weight Distribution



Volume Distribution



Heat Transfer: ENG + HTF + HXT; Structure: Liner + CF; Misc.: BOP + SMT; Metal Hydride: HTMH + Pores + H_2

Acceptable Thermodynamic Map

- ΔH<21 kJ/mol, ΔS range depends on ΔH: 33-103.6 J/mol.K

Kinetic Requirements

- Material "B": ΔH=14.8 kJ/mol, ΔS=77.2 J/mol.K, E_A=45 kJ/mol
- τ_d: Time to discharge HPMH from X_{max} to X_{min} at 60°C, 5 atm backpressure
- τ_c: Time to charge HPMH from X_{min} to X_{max} at 60°C, 410 bar backpressure

FY2016 Collaborations

Physical Storage	PNNL Team: 700-bar tank performance (ST101) Ford: Alternate tank design concepts
Metal Hydrides	ORNL: reverse engineering of high-pressure metal hydrides, acceptability envelope
Sorbents	Ford, LANL: Material properties of sorbents, reverse engineering, acceptability envelope
Chemical Hydrogen	LANL, PNNL: Material properties of chemical hydrogen storage materials, reverse engineering, acceptability envelope
Off-Board Fuel Cycle Efficiency	ANL (H2A Group), ANL (HDSAM)
Off-Board Cost	ANL (H2A Group), ANL (HDSAM)
On-Board Cost	Strategic Analysis Inc (SA)
SSAWG	DOE, HSECoE (LANL, PNNL, SRNL, UM), OEMs,Tank Manufactures, SA

- Argonne develops the storage system configuration, determines performance, identifies and sizes components, and provides this information to SA for manufacturing cost studies

Proposed Future Work

Physical Storage

- Validate ABAQUS model against cryogenic burst test data for cold gas storage (PNNL collaboration)
- MultiMech/ABAQUS simulation of CF composite performance degradation due to void defects, fatigue performance due to crack initiation and growth (Materia/Spencer Composite collaboration)
- Validate impact damage model and calibrate fatigue model against room temperature tank data (PNNL/HL collaboration)
- Support on-going tank projects (graded CF structure, conformable design, improved composites, low-cost glass fibers)
- Independently identify potential of cryo-cH_2 systems in fleet applications (such as buses and waste trucks) with particular focus on dormancy

Material Based Storage

- Analyze system performance with compacted sorbents using HSECoE data for materials and prototypes
- Expand system analysis of hydrogen storage in high-pressure metal hydrides
- Wrap up validation of chemical hydrogen storage material and system models
- Provide system-level support to new projects on material discovery projects

Document models and publish papers in IJHE

Project Summary

Relevance:	Independent analysis to evaluate on-board and off-board performance of materials and systems
Approach:	Develop and validate physical, thermodynamic and kinetic models of processes in physical and material-based systems Address all aspects of on-board and off-board targets including capacities, rates and efficiencies
Progress:	Established new 2015 status performance metrics for 700-bar cH_2 storage tanks: 1.40 kWh/kg gravimetric capacity, 0.81 kWh/L volumetric capacity, 97 kg T700/resin composite. Potential to further reduce CF requirement: 5-7% with ALD and AWS, 20% with T720 CF/epoxy, 2-5% with GF in innermost layer Determined the ΔH vs. ΔS thermodynamic map for MHs to match performance of 700-bar storage system with 47% less CF Conducted reverse engineering to determine the HPMH H-capacity (5.8%) and charge/discharge kinetics for use in a 350-bar hybrid tank.
Collaborations:	SSAWG, HSECoE, Ford, LANL, PNNL, SA
Future Work:	Propose, analyze and validate methods of reducing cost of CF wound storage tanks Validate models for heat transfer and H_2 uptake models in compacted sorbents, high-pressure metal hydrides Provide system-level support to new material discovery projects

Reviewer Comments

Generally favorable reviews with the following comments/recommendations

- Physical storage and methods to reduce CF material and cost should be emphasized over validating HSECoE models that will not be implemented
- Experimental validation of the analyses conducted in this project is an important area that needs more emphasis
- Not clear what is meant by “determine favorable properties of unstable room-temperature metal hydrides”
- For future planned analysis on the tanks, continue to create models that are thorough

FY16 work scope consistent with above recommendations

√ This year’s analysis of the alternate tank design concepts revealed opportunities to further reduce carbon fiber amount by 5 – 7%

√ We work closely with experimental programs to validate our analyses (e.g., validation of ABAQUS model with PNNL tank data, sorbent models with HSECoE data for MOF-5 isotherms and thermal conductivity)

√ In-depth analysis of high-pressure metal hydrides was presented in this year’s accomplishments.

√ Our planned analysis on tanks will integrate ABAQUS with MultiMech for a two-way coupled multi-scale finite element analysis to evaluate composite performance due to void defects and failure/fatigue analysis.

Technical Back-Up Slides

Publications and Presentations

Journal Publications

R.K. Ahluwalia, J.K. Peng, and T.Q. Hua, "Sorbent Material Properties for On-board Hydrogen Storage for Automotive Fuel Cell Systems," International Journal of Hydrogen Energy. 40 (2015) 6373-6390.

Book Chapters

R.K. Ahluwalia and T.Q. Hua, "Pressurized Systems," Chapter 15 in Data, Facts and Figures on Fuel Cells, Detlef Stolten and Remzi and Nancy Garland (Editors), Wiley-VCH, 2016, 143-148.

R.K. Ahluwalia and T.Q. Hua, "Onboard Safety," Chapter 18 in Fuel Cells Data, Facts and Figures, Detlef Stolten and Remzi Samsun and Nancy Garland (Editors), Wiley-VCH, 2016, 177-182.

R.K. Ahluwalia, J.K. Peng, and T.Q. Hua, "Implementing Hydrogen Storage Based on Metal Hydrides," Chapter 32 in Hydrogen Science and Engineering, Materials, Processes, Systems and Technology, Vol 2, Detlef Stolten and Bernd Emonts (Editors), Wiley-VCH, 2016, 791-808.

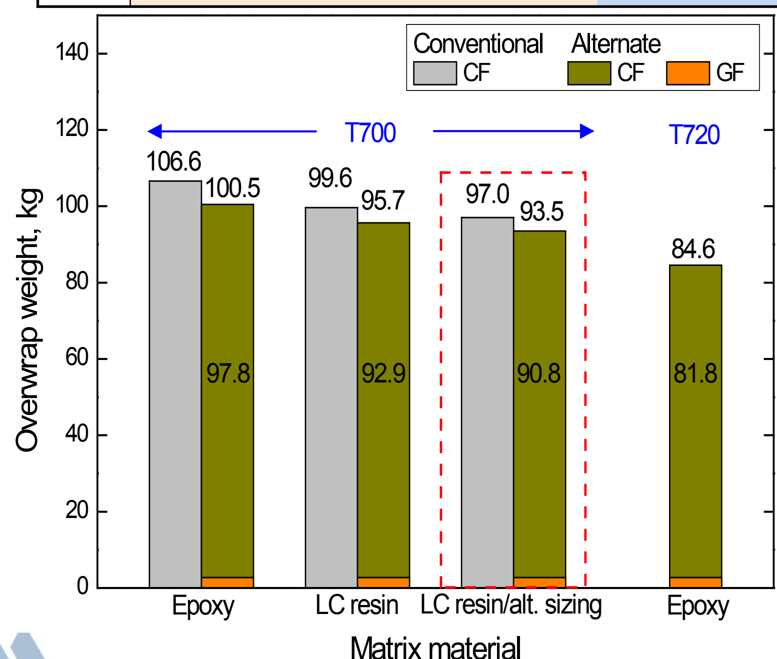
Presentations

H.S. Roh, T.Q. Hua, and R.K. Ahluwalia "Modeling of Type IV Hydrogen Storage Tanks and the Toyota Mirai Storage Tank Design," Storage System Analysis Working Group Meeting, November 16, 2015.

R.K. Ahluwalia, T.Q. Hua, J.K. Peng, and H.S. Roh, "System Level Analysis of Hydrogen Storage Options," Hydrogen Storage Tech Team Meeting, Southfield, MI, March 17, 2016

Alternate Tank Designs with Glass Fiber Layer (147 L, L/D = 3)

Tank	Liner	Winding	Boss	GF Layer	Composite	Remarks
7	CONV	CONV	CONV	No	T700/epoxy resin	Reference tank in 2015 storage performance record
11A	ALG	AWS	ABD	Yes	T700/epoxy resin	Alternate reference tank design
8	CONV	CONV	CONV	No	T700/low-cost resin	2015 reference tank design with low-cost resin
12A	ALG	AWS	CONV	Yes	T700/low-cost resin	Alternate tank design with low-cost resin
9	CONV	CONV	CONV	No	T700/low-cost resin/alternate sizing	2015 reference tank design with low-cost resin and alternate sizing
13A	ALG	AWS	ABD	Yes	T700/low-cost resin/alternate sizing	Alternate tank design with low-cost resin and alternate sizing
14A	ALG	AWS	ABD	Yes	T720/epoxy resin	Alternate tank design with T720/epoxy composite



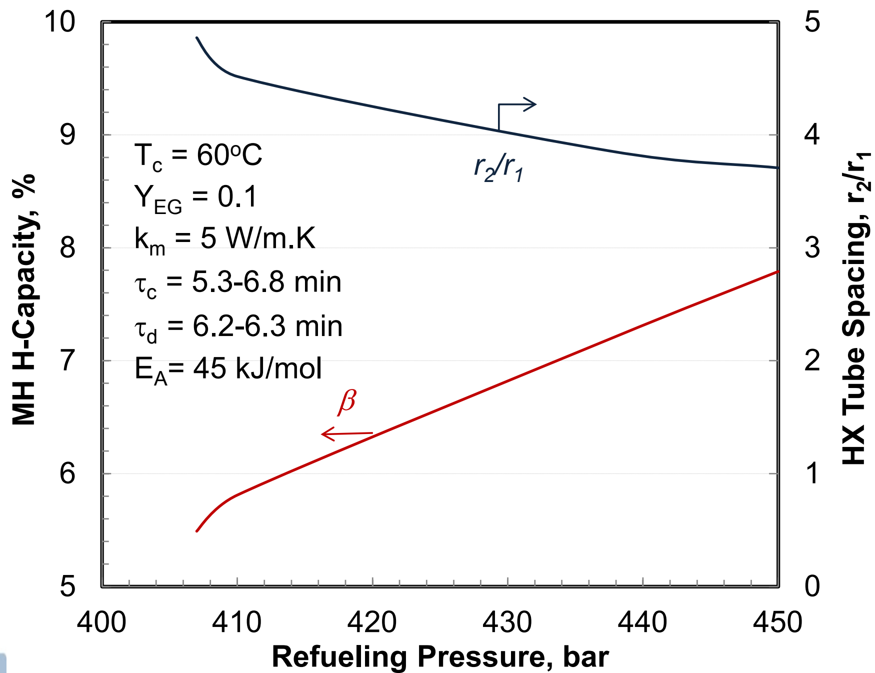
Potential CF reductions with alternate tank design and fiber and GF in innermost layer

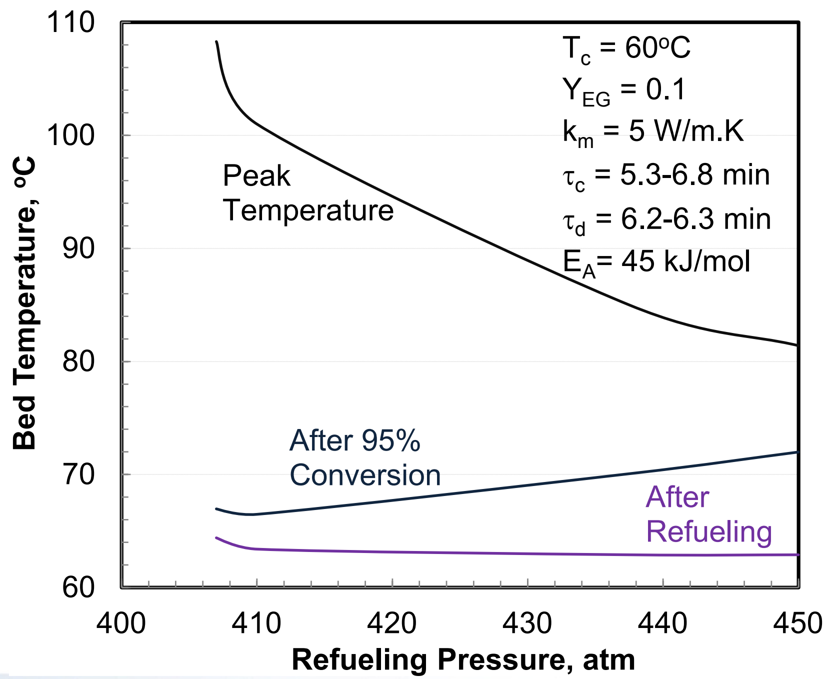
- 8.3% in tanks reinforced with T700/epoxy resin
- 6.4% in tanks reinforced with T700/low-cost resin + alternate sizing
- 23.3% in tanks reinforced with T720/epoxy resin (vs. T700/epoxy resin)

Refueling Pressure

Best to refuel at lowest pressure that leads to 350 bar. This pressure is a function of the kinetic constants.

- The lower the refueling pressure, the higher the transient peak temperature during refueling, and the fewer is the number of heat transfer tubes.
- The optimum pressure may be limited by the allowable bed temperature for HDPE liner.

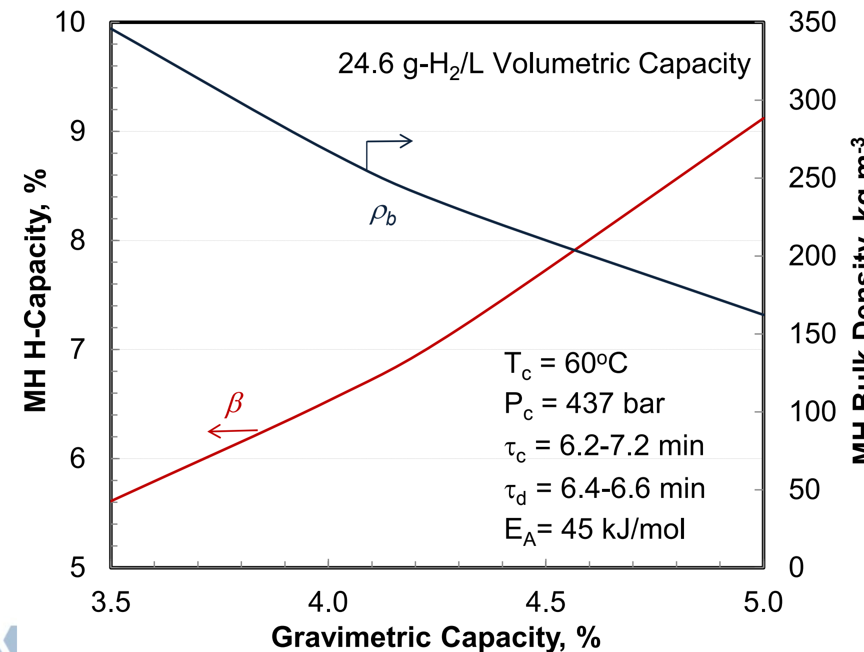


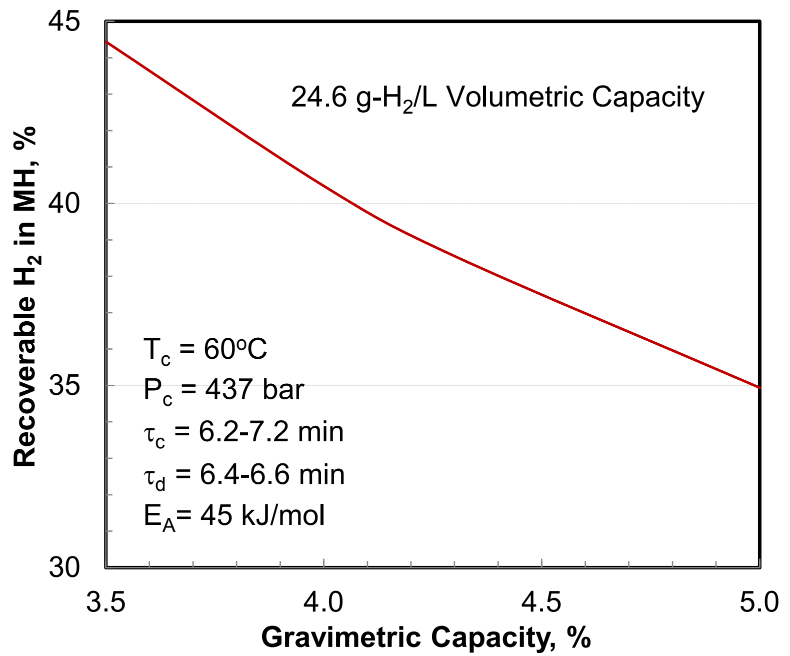


Single Variable Sensitivity Study: Gravimetric Capacity

Material H-capacity has to increase for higher gravimetric capacity, but the recoverable H_2 in metal hydride actually decreases because of lower bulk density (fixed volumetric capacity).

Storage System	Compressed H_2		Hybrid
Storage Pressure	700 bar	350 bar	350 bar
Volumetric Capacity	24.4 g/L	17.7 g/L	24.6 g/L
Gravimetric Capacity	4.2 wt%	5.4 wt%	4.3 wt%
Carbon Fiber	97 kg	62 kg	51 kg





Single Variable Sensitivity Study: Volumetric Capacity

Only a small increase in material H-capacity is needed for higher volumetric capacity, but the recoverable H_2 in metal hydride increases significantly because of higher bulk density (fixed gravimetric capacity).

- External cooling may be required because the heat load during refueling is proportional to the amount of hydrogen stored in metal hydride.

Storage System	Compressed H_2		Hybrid
Storage Pressure	700 bar	350 bar	350 bar
Volumetric Capacity	24.4 g/L	17.7 g/L	24.6 g/L
Gravimetric Capacity	4.2 wt%	5.4 wt%	4.3 wt%
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